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Research paper

# Cut-hole layout decomposition and synthesis to reduce the effect of edge-placement errors

Hongyi Liu, Ting Han, Yijian Chen *

*School of Electronic and Computer Engineering, Shenzhen Graduate School, Peking University, Shenzhen 518055, China*

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ABSTRACT

To overcome the prohibitive barriers of edge-placement errors (EPE) in the cut/block step of complementary lithography, a novel patterning approach is proposed by combining selective etching and alternating-material self-aligned multiple patterning (altSAMP) processes. Unlike the conventional self-aligned multiple patterning (SAMP) processes, the line arrays will be fabricated by the altSAMP technique using two different materials which allow a highly selective etching process to remove one material without attacking the other. To reduce the EPE effect in a cut-hole patterning process, we decompose the holes over the lines made of one material into one mask and the holes over the lines made of the other material into the other mask. Since the targeted-line density for each decomposed mask is half of the original array, more significant EPE effect can be tolerated in each individual cut-hole patterning process. The cut-hole layout decomposition and synthesis algorithms are developed and the experimental results verify their functionality.



## 1. Introduction

1-D layout design has shown a tremendous potential for future IC scaling owing to its simple geometric characteristics and high manufacturability [1]. It facilitates a two-step patterning approach (often called "complementary lithography" [2]) to break the optical resolution limit of current lithography technology. The patterning process starts from a line/trench fabrication step followed by a line-cut/trench-block step to form the desired high-density IC patterns [3]. For instance, the first (line-fabrication) step can be accomplished by a variety of lithography techniques including EUV, self-aligned multiple patterning (SAMP [4–6]), optical multiple patterning, and directed self-assembly (DSA). In particular, the self-aligned multiple patterning and directed self-assembly both have the potential to pattern sub-10 nm (half-pitch) lines with excellent CD uniformity [6–7]. Nevertheless, the second (line-cut or trench-block) step requires a challenging lithography technique with extremely high resolution and overlay accuracy [8–9]. Therefore, to print the randomly distributed cut holes, we often need to decompose them into three or more masks, which in general leads to an NP-complete coloring problem [10–11]. Another difficult engineering issue is the inevitable edge-placement errors (EPE) mainly due to the overlay errors and CD variations of the cut holes and other involved patterns. Apparently, these two barriers will hinder the potential extension of the complementary lithography for future IC scaling if technical solutions fail to be developed.

To overcome the challenge of edge-placement errors, we develop a novel modular technology by combining selective etching and alternating-material self-aligned multiple patterning (altSAMP) processes. In this patterning approach, the altSAMP process offers the density-multiplication function to form dense lines with two different materials, while the selective etching process significantly reduces the edge-placement errors in the line-cut steps, as shown by an example (e.g., an altSAQP process) in Fig. 1. Another advantage is that it simplifies the cut-hole layout decomposition and synthesis algorithm development. Compared with a previously reported SAQP process [7], a potential issue of the altSAQP process scheme is that some of its lines will be defined by the "core space" or "gap space", both of which typically exhibit worse CD uniformity than those lines directly defined by spacers. This paper is one part (part II) of a series of our research work reported recently, and it mainly covers the cut-hole layout decomposition and synthesis algorithm development to solve the edge-placement-error issue. A different paper (part I) is focused on the related process yield and fabrication/material topics [12]).

In Refs. [12–14], a formula to calculate the cut-process yield is reported by introducing a probability-of-failure (POF) concept and

* Corresponding author.
*E-mail address:* chenyj@pkusz.edu.cn (Y. Chen).

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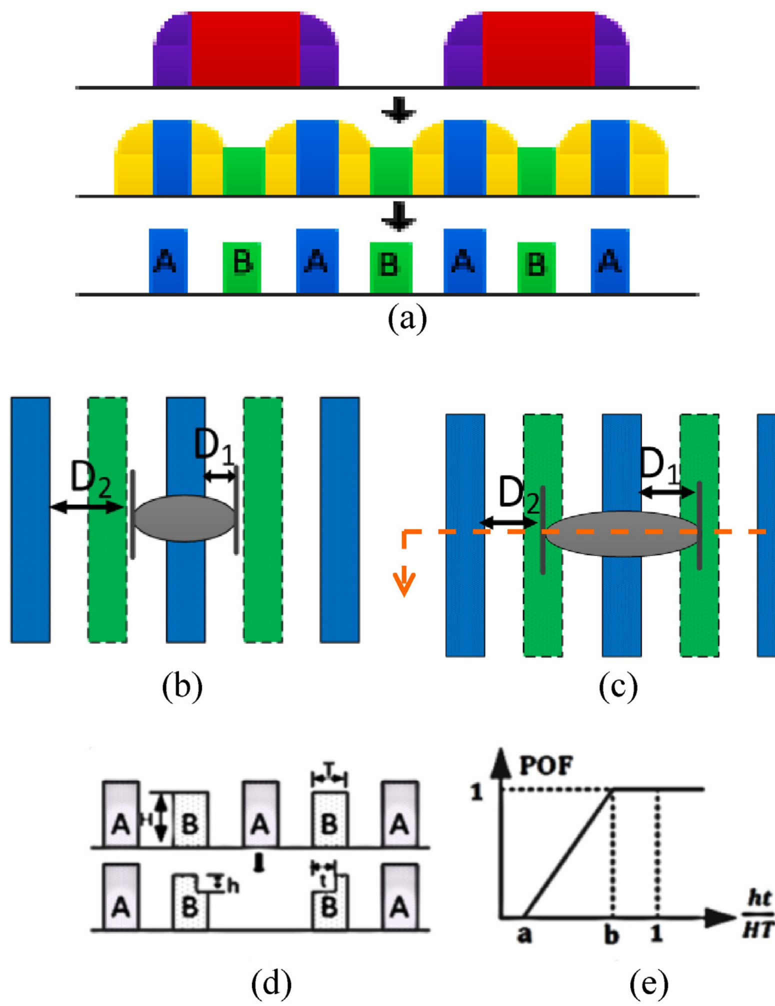


**Fig. 1.** A schematic description of the alternating-material self-aligned quadruple patterning (altSAQP) process and the selective etching process to enhance the cut-process patterning yield. (a) The altSAQP process flow, (b) a target line cut by a hole with an ideal/desired size, (c) a target line and two non-target lines cut by a hole with a non-ideal/enlarged size due to the inevitable process variations, (d) the cross-sectional view (cutting through the position indicated by the arrow in (c)) of the post-etching line structures, (e) POF function of the miscut non-target lines as a function of the ratio of the miscut area to the original area.

assuming a Gaussian probability density function of the overlay errors ($x$) and cut-hole CD variations ($y$):

$$J(x,y) = \frac{1}{2\pi\sigma_1\sigma_2}\cdot exp\left\{-\frac{1}{2}\left[\frac{(x-\mu)^2}{\sigma_1{}^2}+\frac{y^2}{\sigma_2{}^2}\right]\right\}$$

and

$$\text{Yield} = 1 - \iint_D \text{POF}(x,y)\cdot J(x,y)dxdy.$$

POF function is an important concept introduced to correlate the probability of a patterning failure to certain values of overlay error ($x$) and cut-hole CD variation ($y$), as shown in Fig. 1. In the above formula, $J(x,y)$ is the joint probability density function of the overlay errors and cut-hole CD variations. POF value differs significantly in various domains of integration, depending on the complicated physical relation between the probability of a cut failure and these process variations.

The rest of the paper is organized as follows. In section 2, various types of alternating-material self-aligned multiple patterning processes related with the proposed EPE solution are depicted first and their process characteristics and technological merits are discussed. The layout design and decomposition algorithms are described in detail in section 3. The design issues for patterning yield optimization are also addressed. Layout experimental results are shown in section 4 and finally we conclude our paper in section 5.

## 2. The alternating-material self-aligned multiple patterning (altSAMP) processes

Unlike the conventional single-material self-aligned multiple patterning (SAMP) processes [15–18], a line array fabricated by an altSAMP process is made of two different materials (e.g., *A* and *B*) which allow a highly selective etching process to remove one material (ideally) without attacking the other. For example, a line array arranged in an alternating order of *A-B-A-B*… can be fabricated by an alternating-material self-aligned quadruple/octuple patterning (altSAQP/altSAOP) process, while a line array arranged in a quasi-alternating order of *A-B-B-A-B-B*… can be fabricated by an alternating-material self-aligned triple/sextuple (altSATP/altSASP) patterning process. Based on the specific type of the produced line array, we assign the cut holes over the lines made of one material (e.g., *A*) into one mask while collect the cut holes over the lines made of the other material (e.g., *B*) into the other mask. Using the altSAQP process shown in Fig. 2 as an example, we can see that the targeted-line density for each decomposed mask is half of the original array. Therefore each separate cut-hole patterning process can tolerate more edge-placement errors.